JOURNAL OF MATERIALS SCIENCE 19 (1984) 768–776

Role of strain-rate and phase boundary geometry on the deformation behaviour of two-phase bicrystals of alpha–beta brass

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Tensile testing was carried out at various strain-rates using alpha–beta brass two-phase bicrystal specimens having two types of boundary geometries, currugated and flat. The corrugated boundary was more effective in blocking the propagation of slip from alpha to beta phase. A strain-rate sensitivity was found in all specimens regardless of boundary geometry. At low strain-rate, both boundary types were found to be ineffective barriers to the propagation of slip. At high strain-rates both boundaries fully resisted the passage of deformation. At low strain-rates coarse slip was observed, while at high strain-rates fine slip occurred in the alpha phase.

1. Introduction

A large percentage of engineering materials in use consist of more than one phase. The mechanical properties and deformation mechanisms of these inhomogeneous two-phase materials are of considerable practical importance. The properties of two-phase materials depend on the properties of the individual phases, their distribution, the volume fractions of phases present, and on the nature and geometry of phase boundaries. To facilitate the understanding of the basic mechanisms involved in the deformation of two-phase alloys, the number of variables must be minimized. An ideal fundamental unit for studying the mechanical behaviour of a two-phase material would seem to be a single crystal of one phase joined to a single crystal of the other phase. Such a unit was originally named "two-phase bicrystal" by one of the authors of this paper [1]. Growth of stable two-phase bicrystals of alpha–beta brass was also pioneered in the principal investigator's laboratory, by using specialized heat-treatment schedules. The important features concerning these specimens is that the interphase boundary produced is extremely sharp (<1 μm) and stable, similar to that in real two-phase materials. Initial deformation studies on such fundamental units have already been reported [2]. These studies employed a series type of bicrystal where the phase boundary was normal to the tensile axis. Under such loading, alpha, beta and boundary region experience the same stress due to the externally applied load.

Another method of obtaining alpha–beta brass bicrystal by diffusion bonding has been developed by Eberhardt *et al.* [3]. Utilizing a similar procedure, bicrystals of alpha–beta brass have been grown and mechanically tested using iso-axial specimens at specific strain-rates [4–12]. Under such loading conditions strain in alpha and beta crystals have to be the same and the boundary does not experience any stress due to the externally applied loading. Interface sliding, fatigue, and interface structure of such bicrystals are also reported [13–17]. Diffusion bonded interphase boundaries however are neither sharp nor stable. Such bicrystals will be in a meta-stable state, since they are obtained by ice-water quenching of diffusion-bonded specimens [4]. The regions near a phase boundary produced by such a process will ultimately recrystallize [18].

The purpose of this investigation is to study the

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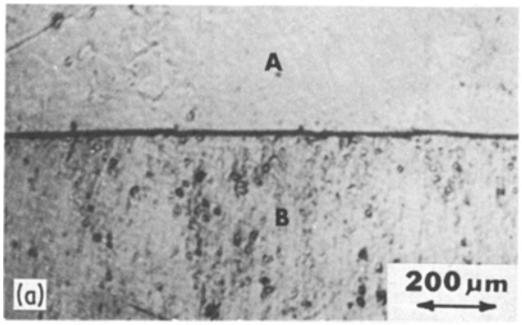

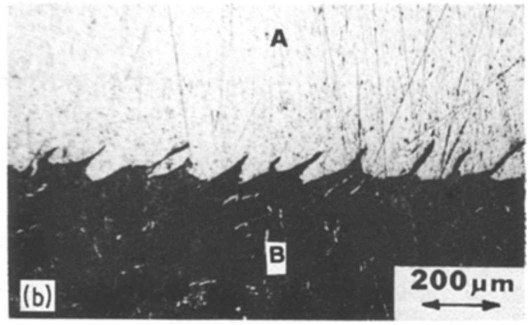

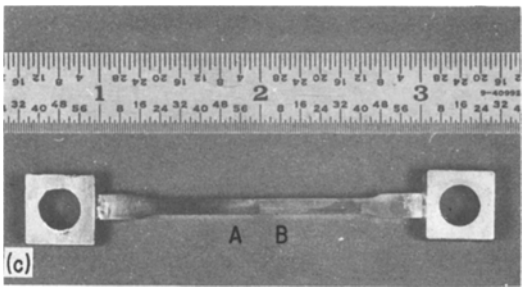

Figure 1 Alpha–beta brass bicrystals. (a) Flat interface; (b) corrugated interface; (c) tensile specimen (A: alpha; B: beta).

role of boundary geometry, namely flat or corrugated, on deformation at various strain-rates using two-phase bicrystals having sharp and stable phase boundaries.

2. Experimental procedures

The alpha–beta brass bicrystal specimens were prepared by the method described already in the literature using alpha brass (70% copper–30% zinc) single crystals and beta brass (51% copper–49% zinc) stock [1, 2]. The specialized heat treatment schedule used in this procedure produced stable two-phase bicrystals with a phase boundary thickness of less than 1 μm. During the heat treatments, the interface region changes its morphology so as to produce flat or corrugated boundary. Alternatively it may result in oriented duplex or equiaxed two-phase region. Typical flat and corrugated interface geometry chosen for the present study are presented in Figs. 1a and b. Bicrystals with desired boundary geometry were carefully machined so as to produce the tensile specimens by using procedures described elsewhere [2]. A typical tensile specimen is shown in Fig. 1c. Back reflection Laue X-ray method was used to determine crystallographic orientations of the alpha and beta crystals in contact at the boundary. Using this data, Schmidt factor and critical resolved shear stress for initiating slip in beta across the phase boundary were obtained.

Tensile tests were carried out using an Instron testing machine with cross-head speeds ranging from 0.005 to 5.0 cm min^{-1}. The objectives of these tests were to determine the strain-rate sensitivity, and to observe the interaction of slip with the boundary. In this study strain-rate is presented in terms of cross-head speed, since the gauge length was kept constant [3.16 cm]. All the specimens had same length of alpha phase [1.58 cm] and same length of beta phase [1.58 cm] within the gauge length. This facilitated the use of cross-head speed of the Instron testing machine as an indicator of strain-rate. Although the alpha–beta series bicrystals were deformed at selected deformation rates by choosing various cross-head speeds, the specimens deformed first in the softer alpha phase. Only when the plastic deformation of alpha was very heavy did the beta phase deform plastically. Under such conditions the strain-rate can be assumed to be approximately equal to the cross-head speed divided by the gauge length of alpha phase.

3. Results

The tabulated results of the tensile tests are given in Tables I and II. All of the micrographs presented in this section have been identified in the following manner: The tensile axis is shown by arrows and the abbreviation "T.A.". The micrographs presented have all been oriented with the alpha single crystal to the left, designated by "A", and beta phase to the right, designated by "B".

3.1. Flat boundary

Extensive testing was carried out using flat boundary bicrystal specimens and all these specimens exhibited strain-rate sensitivity. At low strain-rates, a correspondingly low stress level is required

TABLE I Tensile test results of bicrystal specimens having a flat alpha–beta phase boundary

Cross-head speed ($cm\ min^{-1}$)	Stress (σ) and strain (ϵ) at which slip progressed through the interface		Resolved shear stress for slip to propagate through the boundary		Maximum stress (σ_{max}) and maximum strain (ϵ_{max}) experienced by the specimen		Specimen condition at maximum stress
	σ ($MN\ m^{-2}$)	ϵ(%)	Alpha $Crss_{\alpha}$ ($MN\ m^{-2}$)	Beta $Crss_{\beta}$ ($MN\ m^{-2}$)	σ_{max} ($MN\ m^{-2}$)	ϵ^*_{max}	
0.005	52.5	20.1	24.2	23.0	106.8	30.9	No fracture
0.2	65.4	32.8	32.1	32.7	65.4	32.8	No fracture
0.3	Slip did not progress through interface		–	–	144.1	82.2	No fracture
0.5	Slip did not progress through interface		–	–	151.2	96.7	Failed in alpha
3.0	Slip did not progress through interface		Slip in beta away from the interface at stress = 121.52 $MN\ m^{-2}$, strain = 89.37%		140.1	123.5	Failed in alpha
5.0	Slip did not progress through interface		–	–	118.4	120.4	No fracture

*Strain values are based on the assumption that all the deformation was accommodated in the alpha phase.

for slip propagation from alpha across the phase boundary. With increasing strain-rate, the level of stress to cause slip propagation across the boundary also increases. At high rates, slip does not progress through the flat boundary.

Optical micrographs of a specimen tested at a very low cross-head speed of 0.005 $cm\ min^{-1}$ showing the progressive propagation of slip passing through the flat boundary is shown in Figs. 2a, b and c. The first progress of deformation across the flat phase boundary is shown in Fig. 2a. This occurred at a low stress level, as shown in Table I. Evidence of cross-slip build-up in alpha near the flat boundary prior to the progress of slip through the boundary is clearly evident. At a higher stress level, more deformation has propagated across the boundary, and the cross-slip build-up is more extensive as shown in Fig. 2b. At still higher stress levels, coarse slip in the alpha phase occurs and the cross-slip build-up is more intense and is closer to the flat boundary. Extensive progress of slip through the interface occurs as shown in Fig. 2c.

At this low strain-rate the slip that progresses through the flat phase boundary seems to form

TABLE II Tensile test results of bicrystal specimens having a corrugated alpha–beta phase boundary

Cross-head speed ($cm\ min^{-1}$)	Stress (σ) and strain (ϵ) at which slip progressed through the interface		Resolved shear stress for slip to propagate through the boundary		Maximum stress (σ_{max}) and maximum strain (ϵ_{max}) experienced by the specimen		Specimen condition at maximum stress
	σ ($MN\ m^{-2}$)	ϵ(%)	Alpha $Crss_{\alpha}$ ($MN\ m^{-2}$)	Beta $Crss_{\beta}$ ($MN\ m^{-2}$)	σ_{max} ($MN\ m^{-2}$)	ϵ^*_{max}	
0.01	124.9	108.5	62.1	58.7	124.9	108.5	No fracture
0.05	Slip did not go through interface		Slip in beta away from the interface at stress = 115.4 $MN\ m^{-2}$, strain = 60.4%		140.1	123.5	No fracture
0.5	123	81.3	64	62.82	123	81.3	No fracture
1.0	Slip did not go through interface		-	-	91	42.5	No fracture

*Strain values are based on the assumption that all the deformation was accommodated in the alpha phase.

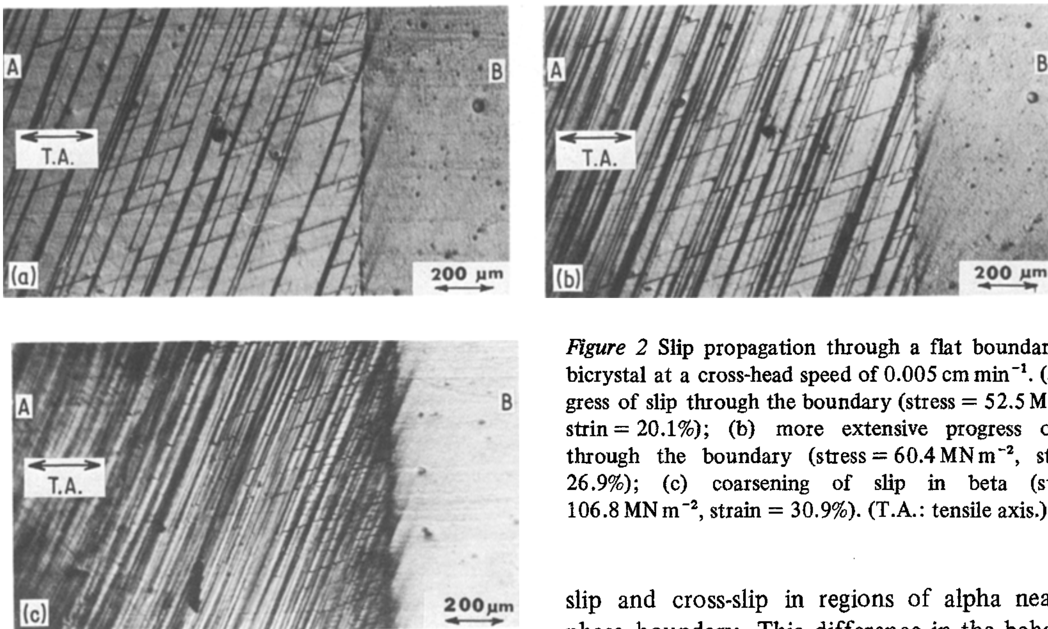

Figure 2 Slip propagation through a flat boundary of a bicrystal at a cross-head speed of 0.005 cm min^{-1}. (a) Progress of slip through the boundary (stress = 52.5 MN m^{-2}, strin = 20.1%); (b) more extensive progress of slip through the boundary (stress = 60.4 MN m^{-2}, strain = 26.9%); (c) coarsening of slip in beta (stress = 106.8 MN m^{-2}, strain = 30.9%). (T.A.: tensile axis.)

deformation zones on the other side of the boundary in the beta phase. The increase in the size of these initiation zones is depicted in Figs. 3a and b. Features such as the increased amount of cross-slip close to the boundary, which is closely associated with the progress of deformation through the interface, can be clearly observed in these figures. Inspection, especially of Fig. 3a, shows a deviation in the angle of the slip trace after having progressed through the boundary. At these low strain-rates, the alpha single crystal portion of the bicrystal specimens experiences heavy, coarse slip.

At higher strain-rates, the slip in the alpha portion is finer, and there is less evidence of multiple-slip and cross-slip in regions of alpha near the phase boundary. This difference in the behaviour of the alpha phase may be seen by comparing the slip in Fig. 4a for a specimen tested with a cross-head speed of 0.1 cm min^{-1} with those shown in Figs. 2 and 3 for a specimen tested at cross-head speed of 0.005 cm min^{-1}. Slip is generally of similar character as in the low strain-rate sample, except for the fact that the extent to which it has propagated in the beta phase is considerably less than that for the specimen tested at 0.005 cm min^{-1}.

Another feature that is evident in this, and as well as in many other samples tested at lower strain-rates, is the "saw-tooth" effect created at the flat boundary. This seems to be caused by the slip bands interacting with the flat boundary as shown by Fig. 4a. Fig. 4b shows the slip interac-

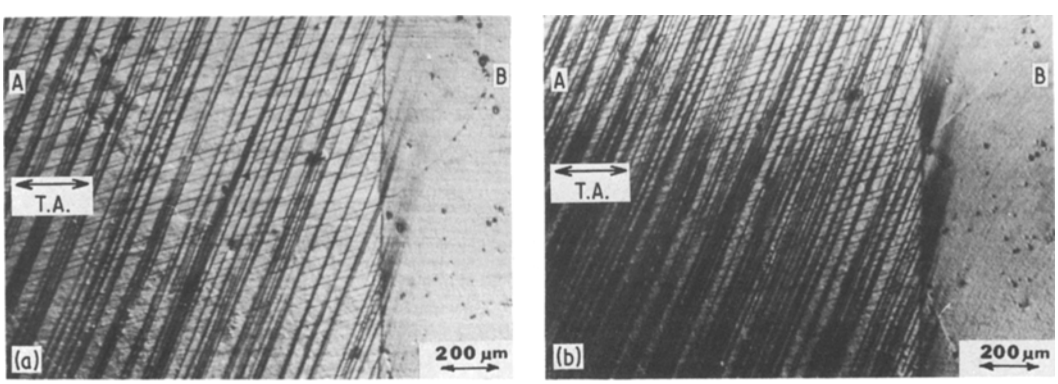

Figure 3 Coarse slip lines in the beta phase initiated by interaction of slip in alpha phase with a flat phase boundary. Cross-head speed is 0.005 cm min^{-1}. Micrographs are of a region different from the one shown in Fig. 2 (a) At a stress level of 52.5 MN m^{-2} (strain = 20.1%); (b) at a stress level of 60.4 MN m^{-2} (strain = 26.9%).

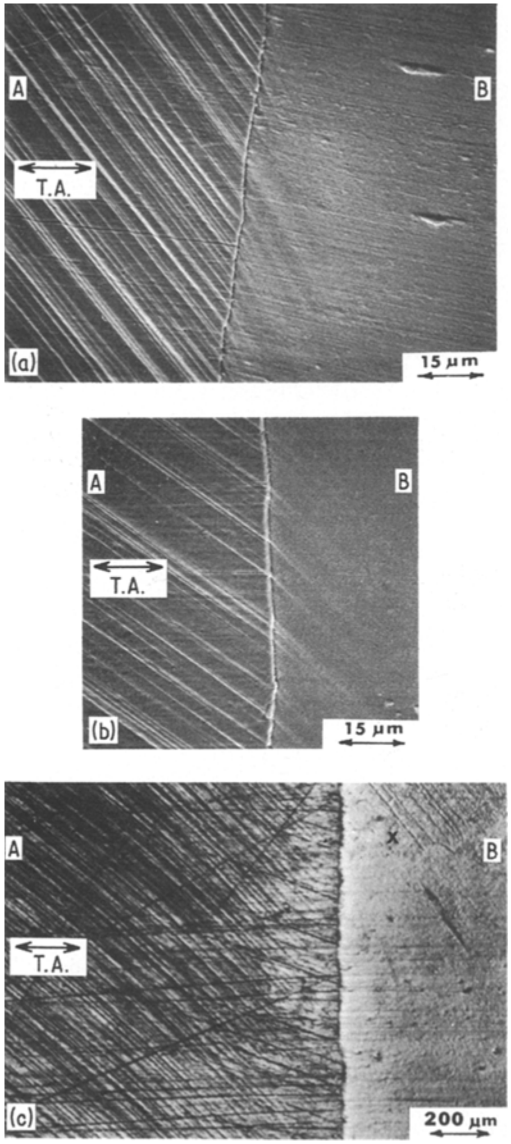

Figure 4 Interaction of slip in alpha with flat phase boundary at various strain-rates. (a) Cross-head speed = 0.1 cm mim^{-1}. Stress = 109.2 MN m^{-2}, strain = 35.1%. (b) Cross-head speed = 0.2 cm min^{-1}. Stress = 65.4 MN m^{-2}, strain = 32.8%. (c) Cross-head speed = 3.0 cm min^{-1}. Stress = 134.3 MN m^{-2}, strain = 112.1% (No propagation of slip occurred through the boundary. Fine slip in beta occurred in a region away from the boundary at stress = 121.5 MN m^{-2}, strain = 89.3%.)

tion with a flat boundary for a specimen tested using a cross-head speed of 0.2 cm min^{-1}. Fine, closely spaced slip lines in bands initiate slip through the flat bicrystal boundary. At a later stage of deformation, slip in the alpha phase is much heavier, but still predominately in bands, and it is accompanied by cross-slip within the bands. The specimen shown in Fig. 4c was tested using a cross-head speed of 3.0 cm min^{-1}. The fine slip in the alpha phase even after heavy deformation, which seems to be characteristic of the alpha phase behaviour at high strain-rates, is clearly evident. Some evidence of multiple slip is present in the high strain-rate specimens, but little or no cross-slip in the boundary regions was observed. In the region labelled "X" in the beta phase, fine slip was observed. This slip propagated towards the phase boundary at higher stress levels, and no slip was found to progress through the flat boundary from the alpha phase.

A specimen having a flat boundary was tested with a cross-head speed of 5.0 cm min^{-1}, and just as in the specimen tested at 3.0 cm min^{-1} no slip progressed through the interface, even at maximum stress levels. Rather, slip was initiated in the beta phase away from the boundary.

3.2. Corrugated boundary

Several specimens having corrugated type of bicrystal boundary were tested to evaluate its effect on the deformation behaviour. Such a boundary will experience shear stress in certain regions of the boundary. The results of these tests are presented in Table II.

Optical micrographs of specimens tested at two different cross-head speeds of 0.01 cm min^{-1} and 0.5 cm min^{-1} are presented in Figs. 5a and b. In general, the nature of slip in the alpha phase is coarse and rather heavy at lower strain-rates, and is considerably finer with an absence of cross-slip at high strain-rates. As shown by Fig. 5a for a specimen tested at a cross-head speed of 0.01 cm min^{-1}, slip in the alpha phase is rather coarse, and multiple slip systems are operative near the boundary. When slip progresses through the phase boundary, it is very fine or occurs in diffuse bands. The slip band traces then continue only for short distances in the beta phase before they are diffused and stopped.

The micrograph of a specimen tested using a cross-head speed of 0.5 cm min^{-1}, given in Fig. 5b, shows some fine scale cross-slip build-up at some finite distance from the boundary. Some very fine slip features may also be observed in the corrugated alpha phase regions of the boundary, but no slip progressed through the interface of this specimen. Rather, slip was initiated in the beta phase

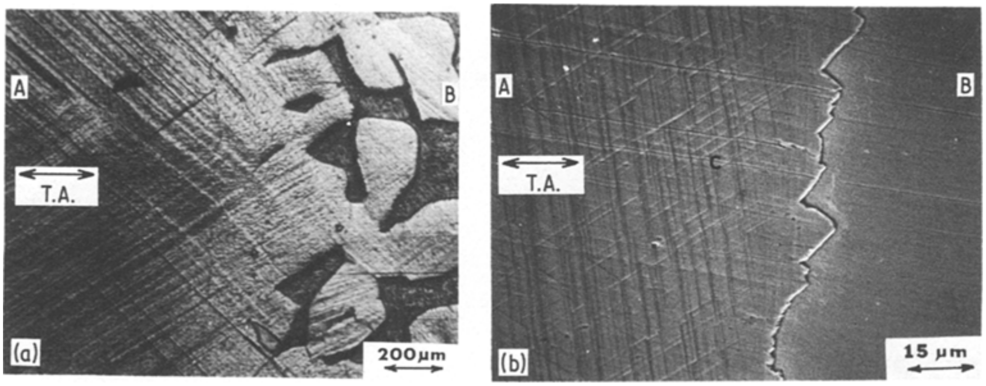

Figure 5 Interaction of slip in alpha with corrugated phase boundary at various strain-rates. (a) Cross-head speed = 0.01 cm min^{-1}. Stress = 124.9 MN m^{-2}, strain = 108.5% (progress of slip through the interface occurred at stress = 106.53 MN m^{-2}, strain = 53.1%). (b) Cross-head speed = 0.5 cm min^{-1}. Stress = 123 MN m^{-2}, strain = 81.3% (note cross-slip in alpha phase at c).

away from the boundary. With the higher strain-rate, slip in the alpha phase, as observed before, is finer, and there is little evidence of any cross-slip build-up in the vicinity.

In a specimen tested using a cross-head speed of 1.0 cm min^{-1}, slip did not propagate through the boundary – rather slip was initiated in the beta phase away from the boundary. Slip interaction in the alpha phase with the boundary is much less than that experienced at lower strain-rates. Very fine slip was observed in the extended portions of the corrugated boundary, but no slip lines progressed across the phase boundaries into the beta phase. At higher strain-rates, the alpha crystal portion of the bicrystal test specimen is subjected to large, heavy deformations and acquires a heavily rumpled appearance. For specimens in which slip was initiated in the beta phase in a region away from the boundary, two types of slip lines were observed to occur in the beta phase. At low strain-rates this slip in the beta phase is fine or diffused, and at higher strain-rate it tends so be coarse.

4. Discussion

4.1. Strain-rate effects

When slip approaches a boundary, it will initially do so in the form of single isolated slip lines. The boundary acts as a barrier and stops the progress of slip, at least temporarily, and dislocations pile up. This pile-up creates a localized stress concentration in the nearby region of the adjacent phase. If the applied stress does not increase sufficiently, the back stress created by the dislocation pile-up may stop the operation of the dislocation source. Karashima [19] has observed this type of stress concentration and work-hardening caused by dislocation pile-ups in alpha brass.

When the stress concentration reaches a sufficiently high level, the dislocations present in the phase boundary may be forced into the adjacent grain and thereby propagate slip through the boundary [20]. Alternately the high stress concentration in this localized region may activate dislocation sources in regions on the other side of the phase boundary and in effect allow deformation to proceed across the interface into the adjacent region [21–23].

In this study, for all of the samples tested at low strain rates, wide slip bands were observed to interact with the boundary. Dislocations on the individual slip planes of a slip band can form a pile-up. Stresses caused by such pile-ups will complement one another to cause a much higher stress concentration. Such stresses can be relaxed by cross-slipping in alpha. However, double cross-slip can cause dislocation multiplication in parallel slip planes. Although cross-slipping can initially relax the stress concentration resulting from the pile-ups, activation of the newly created sources will produce a large number of dislocations piling up at the boundary in parallel slip planes. When alpha has deformed sufficiently to prevent further cross-slip, relaxation by cross-slip becomes difficult, and deformation must be accommodated in the beta region.

In high strain-rate tests, slip in alpha progressed to the boundary as single slip. As the slip lines become blocked at the boundary, dislocation sources present in parallel slip planes become active. However, multiple slip also takes place in high strain-rate deformation. Dislocations moving in intersecting slip planes can interact with each other and cause jogs. Since the dislocations present in alpha near the interface will have a high density of jogs caused by the intersecting slip, their motion will be restricted. As a result, most of the dislocations present in alpha near the interface region will not be able to cause long-range stress fields because of dislocation pile-ups. Under such conditions, slip propagation through the interface cannot take place. Therefore, in specimens tested at high strain-rates there was no deformation across the boundary, regardless of boundary geometry. Rather, the applied stress level built up until the critical resolved shear stress of the beta phase was reached and the beta phase deformed because of the applied stress in a region away from the phase boundary. At high strain-rates, therefore, the phase boundary region seems to be the strongest part of the bicrystal specimens.

Another factor that has influence on the high strain-rate deformation of these bicrystal test specimens is the behaviour of the beta phase at high strain-rates. The yield stress of beta phase increases when subjected to dynamic loading conditions [24]. An interpretation for the lack of progress of slip through the boundary at high strain-rates can be attempted on the basis of higher critical resolved shear stress for beta at higher strain-rates. However, such an interpretation will have serious drawbacks. In specimens tested at high strain-rates, slipping had started in regions far away from the boundary indicating that the applied stress level was high enough to cause deformation in beta, although slip did not progress through the boundary in the interface region.

4.2. Effects of boundary geometry

In formulating this study it was of interest to develop one type of bicrystal specimen boundary in which the boundary, or portions of it, would be inclined to the tensile axis. Such specimens would be helpful in understanding the role of the relative orientation of the boundary with respect to the tensile axis. In such a boundary geometry, much of the boundary surface would be inclined to the tensile axis to various degrees, and thus any effect that an inclined boundary may have on the passage of deformation across the boundary could be realized. The geometrical features of the boundary obviously play a significant role in the mechanical behaviour of the bicrystals, as noticeable differences were observed during the course of the study. The corrugated type of boundary geometry has been found to be more effective in preventing slip propagation from the alpha phase to the beta phase than the flat boundary. The entire slip band interacts with the boundary surface in the flat boundary geometry, whereas with the corrugated boundary only a portion of the total boundary surface is oriented favourably for the slip band to interact effectively to propagate deformation into the beta phase, as shown in Figs. 6a and b.

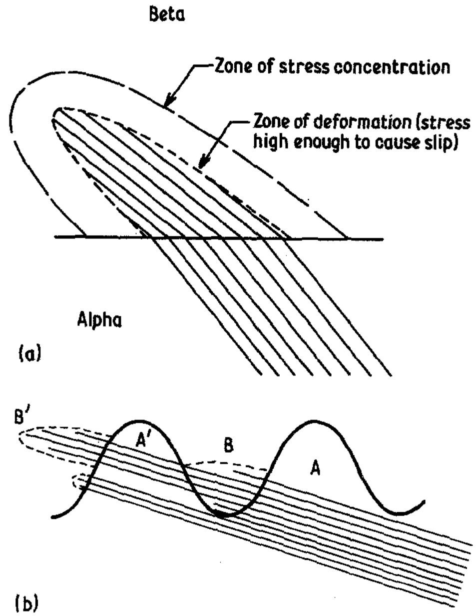

Figure 6 Interaction of slip in alpha with phase boundary. (a) Flat phase boundary. (b) Corrugated phase boundary.

Once through the boundary, however, further slip propagation is more difficult for two reasons. First, the motion of the superlattice dislocations in the beta phase is more difficult [25], and the stress concentration tends to decrease rapidly with increasing distance from the boundary. As a result, there is a strong tendency for the slip propagation to stop [26]. Secondly, as the mode given in Fig. 6b illustrates, each time slip propagates from alpha (A) into beta (B) and emerges again in adjacent alpha (A′) it will invariably be much finer due to the resistance experienced at the AB and BA′ interfaces. When such fine slip interacts with the next interface (A′B′) it may be totally blocked. In addition, the slip line length in the alpha phase (A′) necessary to cause an effective dislocation pile-up at the interface (A′B′) has decreased, and there will be a corresponding decrease in the severity of the stress concentration. Further, where the interface is inclined to the tensile axis, it experiences shear stresses from the applied loading, and slip propagation across interfaces under such conditions have been found to be difficult [27].

4.3. Slip in the beta phase

In regions where slip was observed to have progressed across the boundary, a zone of deformation was formed in regions of the beta phase adjacent to the boundary. Once sufficient stress concentration was created owing to the dislocation pile-up at the barrier, slip proceeded into the beta phase. Observations made during the course of this study, and by Honeycombe and Boas [26], who studied the deformation of alpha–beta brass, show that the deformation does not proceed vary far into the beta phase. It is stopped within a short distance of the boundary. Although slip lines in beta are prominent very near the boundary, they rapidly become very diffuse at points away from the boundary.

The slip propagation in the beta phase requires the movement of superlattice dislocations as in a typical caesium chloride structured material. These superlattice dislocations are composed of two partial dislocations joined to one another by an anti-phase boundary. Because of the geometry of this superlattice dislocation, it must move as a whole unit since the partial dislocations are connected to one another by the anti-phase boundary. As a result, their motion is difficult and requires a high stress [25]. The high stress concentration developed at the phase boundary which allows deformation to proceed through the boundary is quite limited in its extent into the beta region. Therefore, as any given slip line proceeds from alpha across the boundary and into beta, it will proceed only to a limited extent. The extent depends on the level of the stress concentration, which is a function of the distance from the boundary. When the slip line in beta reaches a position at which the stress concentration is insufficient to continue slip propagation, it will stop.

5. Summary and conclusions

1. Among the two types of boundaries considered in this study, the flat type of interface structure provides less resistance for the progress of slip across the phase boundary. Regardless of the type of boundary geometry all of the bicrystals were found to be strain-rate sensitive.

2. At lower strain-rate tests, especially with specimens having flat interfaces, extensive cross-slip near the boundary was observed. The cross-slip appears to help in creating wider slip bands in the alpha phase regions near the interface.

3. Higher strain-rates tend to form very fine slip in alpha by activating many dislocation sources on numerous planes. These result in multiple slip near the boundary, which retards the motion of a large portion of the dislocations and consequently makes the initiation of deformation across the boundary into beta regions very difficult.

4. In specimens having corrugated boundaries, slip is usually initiated at high strain-rates in the beta phase in a region away from the boundary, indicating that the interface regions are very effective barriers to slip, especially in the absence of specific relative crystallographic orientations between alpha and beta grains.

5. Irrespective of the nature of the boundary, no void formation or crack nucleation was observed at the interface due to slip interaction in either type of boundary studied in the present investigation.

6. The results on flat boundary bicrystals suggest that the dislocation sources in the beta phase near the phase boundary become operative due to the additional stress caused by dislocation pile-ups formed at the boundary in the alpha phase region along with applied stress. However, phenomena such as initiation of slip at regions far away from the boundary indicate that the activation of sources in beta region is more likely than a mechanism which will utilize grain boundary sources for initiation of slip. Deformation of the beta phase seem to be controlled by the difficulty in propagation of slip in the beta phase, as a result of its superlattice structure.

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Received 1 June
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